Inclusive J/psi production in Xe-Xe collisions at root s(NN)=5.44 TeV

Acharya, S.; Acosta, F.T.; Adamova, D.; Adolfsson, J; Aggarwal, MM.; Aglieri Rinella, G.;
Agnello, Maria; Agrawal, N.; Ahammed, Z.; Ahn, S.U.; Aiola, S.; Akindinov, A.; Al-Turany, M.;
Alam, SN; Albuquerque, DSD; Aleksandrov, D.; Alessandro, B; Molina, Rafael A.; Ali, Yusuf;
Alici, A.; Alkin, A.; Alme, J.; Alt, T.; Bearden, Ian; bsm989, bsm989; Bilandzic, Ante;
Gajdosova, Katarina; Gaardhøje, Jens Jørgen; Bourjau, Christian Alexander; Ozelin De Lima
Pimentel, Lais; Thoresen, Freja; Nielsen, Børge Svane; Zhou, You; Chojnacki, Marek;
Christensen, Christian Holm

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Inclusive $J/\psi$ production in Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV

ALICE Collaboration

Abstract

Inclusive $J/\psi$ production is studied in Xe–Xe interactions at a centre-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.44$ TeV, using the ALICE detector at the CERN LHC. The $J/\psi$ meson is reconstructed via its decay into a muon pair, in the centre-of-mass rapidity interval $2.5 < y < 4$ and down to zero transverse momentum. In this Letter, the nuclear modification factors $R_{AA}$ for inclusive $J/\psi$, measured in the centrality range 0–90% as well as in the centrality intervals 0–20% and 20–90% are presented. The $R_{AA}$ values are compared to previously published results for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and to the calculation of a transport model. A good agreement is found between Xe–Xe and Pb–Pb results as well as between data and the model.

The study of the production of quarkonium states plays an important role in the characterization of the properties of the Quark-Gluon Plasma (QGP) [1]. This state of matter, where quarks and gluons are not confined into hadrons, can be produced in heavy-ion collisions at ultrarelativistic energies. Quarkonia are bound states of heavy quark-antiquark pairs (charmonia, c̄c and bottomonia, b̄b) and their production rate is significantly affected by the QGP. In particular, the color force responsible for the binding of heavy quarks is expected to be screened in the QGP, leading to a suppression of quarkonium production which can be related to the initial temperature of the system [2,3]. In addition, at very high energies, such as those available at the LHC, the abundant production of charm-anticharm pairs leads to a recombination process, which may occur both in the QGP phase or when the system cools down and hadrons are formed out of the free quarks and gluons [4,5]. The study of the interplay between suppression and recombination processes offers the possibility of a quantitative investigation of the existence of colorless bound states of heavy quarks in the QGP.

An extended set of results was obtained for the $J/\psi$, a charmonium state with quantum numbers $J^{PC} = 1^{−−}$, at LHC energies ($\sqrt{s_{NN}} = 2.76$ and 5.02 TeV) in Pb–Pb collisions [6–12]. Comparison of these results to theoretical models [13–17] and to lower energy data [18,19] favors the picture described above. The study of the collision of nuclei lighter than Pb may give additional important information on the relative contribution of suppression and recombination mechanisms.

A step in this direction is performed in this Letter, where first results on $J/\psi$ production at LHC energies in Xe–Xe, a collision system ($A_{Xe} = 129$) lighter than Pb–Pb ($A_{Pb} = 208$), are presented.

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1 In the ALICE reference frame, the muon spectrometer covers a negative $\eta$ range and consequently a negative $y$ range. We have chosen to present our results with a positive $y$ notation.
Fig. 1. Fits to invariant mass distributions of opposite-sign dimuons, for 0–90% Xe–Xe collisions. In the left panel, the result of a fit to the raw invariant mass spectrum is shown, while in the right panel the fit to the same distribution after subtraction of the mixed-event background is presented. The fit curves shown in blue represent the sum of the signal and background shapes, while the red lines correspond to the J/ψ signal and the blue dashed ones to the background (see text for details). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

given threshold, which is set at the trigger level. In addition, the V0 [23], a set of scintillator detectors covering 2.8 < η < 5.1 and −3.7 < η < −1.7, is used to define the minimum bias (MB) interaction trigger via a coincidence of signals at positive and negative η values. The V0 is also used for the centrality estimate via a fit of the distribution of the total signal amplitudes in the framework of the Glauber model [21]. The reconstruction of the primary collision vertex is carried out in the two layers of the Silicon Pixel Detector (SPD), the innermost part of the Inner Tracking System of the experiment [26], covering |η| < 2 and |η| < 1.4 respectively. Finally, rejection of non-hadronic Xe–Xe collisions is performed using the Zero Degree Calorimeters (ZDC) [27], which identifies electromagnetic interactions, while the V0 detects beam-gas collisions occurring outside the nominal interaction point region.

The data analyzed in this Letter are taken with a trigger formed by the coincidence of the MB trigger signal and of at least one muon triggered in the muon spectrometer, with a pT = 0.5 GeV/c threshold. The definition of the trigger is less restrictive than the one usually adopted for Pb–Pb data taking (1 GeV/c threshold and two detected muons), due to the much smaller instantaneous luminosity for Xe–Xe collisions. Standard selection criteria [10] are then applied to such events and to the muon candidates. In particular, it is required (i) that two opposite-sign tracks reconstructed in the tracking chambers of the muon spectrometer are matched to track segments in the trigger system, (ii) that both muons belonging to the pair (dimuon) have −4 < ηµ < −2.5, and (iii) that their transverse position Rabs at the end of the hadron absorber of the muon spectrometer satisfies the condition 17.6 < Rabs < 89.5 cm.

Finally, the reconstructed dimuon should lay in the fiducial rapidity region of the muon spectrometer, 2.5 < y < 4.

The nuclear modification factor RAA for the collision system under study is defined, for the centrality interval i, as

\[ R_{AA}^i = \frac{N_{i}^{J/\psi}}{BR_{J/\psi \rightarrow \mu^+\mu^-} N_{MB}^{i} A_s^i (T_{AA}^i / c)^{pp} / A_{J/\psi}^{pp}}, \]

where N_{i}^{J/\psi} is the number of detected J/ψ in the i-th centrality interval, BR_{J/\psi \rightarrow \mu^+\mu^-} = (5.96 ± 0.03)% is the branching ratio of the dimuon decay channel [28], N_{MB}^{i} is the number of MB events corresponding to the analyzed triggered event sample, A_s^i is the product of the detector acceptance times the reconstruction efficiency, (T_{AA}^i) is the average nuclear thickness function [29], and A_{J/\psi}^{pp} is the inclusive J/ψ cross section for pp collisions, at the same energy and in the same kinematic range as the Xe–Xe data. Results are given for the centrality interval 0–90% and for the two sub-intervals 0–20% and 20–90%.

Except for the determination of \( A_{J/\psi}^{pp} \), the other quantities entering the definition of RAA are evaluated following the same procedure used for the analysis of the Pb–Pb data sample and detailed in Ref. [10].

The extraction of N_{i}^{J/\psi} is performed with two different approaches. In the first, the raw opposite-sign dimuon invariant mass distribution is fitted with a superposition of resonance and background shapes [30], the former being tuned to Monte Carlo (MC) simulations and the latter corresponding to empirical functions. In the second, the background is estimated via a mixed-event invariant mass distribution, obtained from the collected sample of muon-triggered events and subtracted from the raw spectrum [9]. The resulting distribution is then fitted with the sum of a resonance shape and a continuum function accounting for the small residual background component. Due to the low statistical significance of the present data sample, the width of the J/ψ meson, which is usually kept as a free parameter in the invariant mass fits, is fixed to \( A_{J/\psi} = 70 \text{ MeV/c}^2 \), corresponding to the value of this quantity obtained in previous analyses [10,31,32]. For each of the two approaches, several fits were performed varying the fit mass range, the signal and background shapes and the J/ψ width by ±1 MeV/c^2. The obtained value for the centrality interval 0–90% is N_{i}^{J/\psi} = 241 ± 47(stat.) ± 26(syst.), where the central value and the statistical uncertainty correspond to the average of the fit results and to the average of the corresponding statistical uncertainties, respectively. The systematic uncertainty is obtained as the root mean square of the distribution of the N_{i}^{J/\psi} values obtained with the various fits. The corresponding values for the 0–20% and 20–90% centrality sub-intervals are N_{i}^{J/\psi} = 175 ± 42(stat.) ± 23(syst.) and N_{i}^{J/\psi} = 77 ± 20(stat.) ± 7(syst.), respectively.

Fig. 1 shows as an example the results of two fits to the 0–90% Xe–Xe dimuon invariant mass distribution, corresponding to fitting the raw spectrum (left panel) or the mixed-event background subtracted mass distribution (right panel).

The product of the acceptance times the reconstruction efficiency \( A_s \) for J/ψ is evaluated via a MC simulation, based on the GEANT3 transport model [33], which takes into account the
alignment of the muon spectrometer detectors and their efficiency. The input $p_T$ and $y$ distributions for the $J/\psi$ acceptance calculation cannot be tuned directly to data, due to the low integrated luminosity of the data sample. It is therefore assumed that the shape of the $y$ and $p_T$ distributions is similar for different collision systems in centrality intervals corresponding to the same average number of participant nucleons, weighted by the corresponding number of nucleon–nucleon collisions, $\langle N_{\text{part}} \rangle$. The weighting is introduced to take into account that the $J/\psi$ production cross section is proportional to the number of nucleon–nucleon collisions and that therefore the average $N_{\text{part}}$ in wide centrality bins is systematically shifted towards higher values. Following this argument, the differential distributions measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [10] for the 20–40% centrality range are used as input distribution for the MC calculation, since $\langle N_{\text{part}} \rangle_{\text{PbPb,20–40%}}$ is equal, within $\sim 2\%$, to $\langle N_{\text{part}} \rangle_{\text{XeXe,0–90%}}$, estimated via a Glauber MC calculation. The systematic uncertainty on the $J/\psi$ acceptance value due to the choice of the $J/\psi$ rapidity and transverse momentum distributions amounts to 2% and is evaluated by choosing alternative input shapes corresponding to other Pb–Pb centrality ranges.

Concerning the reconstruction efficiency, it slightly depends on the collision centrality, due to the detector occupancy in the muon spectrometer. The effect was evaluated in the analysis of Pb–Pb events [10] by embedding the simulated $J/\psi$ signal into real events corresponding to various centralities. For this analysis, starting from the Pb–Pb results, the decrease in $A_{\text{XeXe,0–90%}}$ with respect to a simulation containing only $J/\psi$ is estimated to be 4.2% (values for 0–20% and 20–90% centrality ranges are 5.5% and 1.6%, respectively). The systematic uncertainty on the reconstruction efficiency is evaluated following the procedure used in Ref. [10], leading to a 3.6% effect.

The resulting value for the product of acceptance times reconstruction efficiency for $J/\psi$ production in 0–90% Xe–Xe collisions is $A_{\text{XeXe,0–90%}} = 0.228 \pm 0.009$(syst.), with a negligible statistical uncertainty.

The normalization factor $N_{\text{NN}}$ is evaluated by multiplying the number of opposite-sign dimuon triggers by a factor $F_{\text{norm}}$, corresponding to the inverse of the probability of having a triggered muon in a MB event. This quantity is computed from the event trigger input information and the level-0 trigger mask. The procedure and the evaluation of the systematic uncertainty are described in Ref. [10]. The obtained value is $F_{\text{norm}} = 2.428 \pm 0.001$(stat.) $\pm 0.024$(syst.).

The reference cross section for the calculation of $R_{AA}$ is obtained starting from the measured value of the inclusive $J/\psi$ cross section in pp collisions at $\sqrt{s} = 5.02$ TeV [10]. This quantity is then corrected to account for the different centre-of-mass energy of the Xe–Xe data, using an interpolation of available ALICE pp results at $\sqrt{s} = 2.76, 5.02, 7, 8$ and 13 TeV [32]. The obtained value is $\sigma_{pp}^{J/\psi} = 5.99 \pm 0.09$(stat.) $\pm 0.30$(syst.) mb$^{-1}$, where the systematic uncertainty contains a small term (0.4%) related to the interpolation procedure, calculated as the maximum spread between results obtained with various interpolating functions [34].

The nuclear thickness function $\langle T_{AA} \rangle$ is evaluated for the various centrality intervals via a Glauber model calculation, and its uncertainty is estimated by varying within uncertainties the density parameters of the Xe nucleus [29,35]. For 0–90% centrality its value amounts to $\langle T_{AA} \rangle = 3.25 \pm 0.25$ mb$^{-1}$, while for 0–20% and 20–90% one obtains $\langle T_{AA} \rangle = 9.90 \pm 0.62$ mb$^{-1}$ and $\langle T_{AA} \rangle = 1.35 \pm 0.14$ mb$^{-1}$, respectively.

Finally, a systematic uncertainty on the definition of the centrality intervals is evaluated by varying the value of the VO signal amplitude corresponding to 90% centrality by $\pm 0.5$% and recalculating correspondingly the centrality intervals.

Table 1 shows a summary of the systematic uncertainties on the $R_{AA}$ measurement for the three analyzed centrality ranges. The main contributions come from the estimate of $\langle T_{AA} \rangle$ and from the signal extraction. The former is dominated by the uncertainty on the surface thickness of the Xe nucleus. The latter, being estimated in a data-driven way as detailed above, may suffer from the statistical limitations of the data sample. The quoted values can therefore be considered to be a conservative estimate.

The $p_T$-integrated nuclear modification factor for inclusive $J/\psi$ production in Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV, measured in $2.5 < y < 4$ and in the 0–90% centrality range, is $R_{AA} = 0.54 \pm 0.11$(stat.) $\pm 0.08$(syst.). This value can be compared with the corresponding one for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, $R^{\text{PbPb}}_{AA} = 0.65 \pm 0.01$(stat.) $\pm 0.04$(syst.) [10]. Their ratio amounts to $0.84 \pm 0.16$(stat.) $\pm 0.13$(syst.), showing that the two values agree within about 8σ. Following the approach of Ref. [5], it can be shown that the Xe–Xe nuclear modification factor for prompt $J/\psi$ could be up to 10% higher (lower) than the inclusive $R_{AA}$ if the non-prompt $J/\psi$ component from the decays of hadrons containing a b quark is not (completely) suppressed. In Fig. 2 the $R_{AA}$ values for 0–20% and 20–90% Xe–Xe collisions are plotted, and compared.
with the centrality dependence of the nuclear modification fac-
tor for Pb–Pb collisions [10]. The latter shows, after a decrease
up to \( N_{\text{part}} \sim 100 \), a saturation at \( R_{\text{AA}} \sim 0.65-0.7 \) towards more
central events, and the two Xe–Xe points are found to be in agree-
ment, within their larger uncertainties, with the Pb–Pb results. The
Xe–Xe and Pb–Pb results are also compared with the calculation of
a transport model by Du and Rapp [13,14]. A close similarity of
the predicted suppression patterns for Pb–Pb and Xe–Xe is observed,
which fairly reproduces the experimental results.

In summary, we have measured inclusive \( J/\psi \) production in
Xe–Xe collisions at \( \sqrt{s_{\text{NN}}} = 5.44 \) TeV. Results on the nuclear mod-
ification factors were given for various centrality selections and
compared to corresponding results for Pb–Pb collisions at \( \sqrt{s_{\text{NN}}} = 5.02 \) TeV and to a theoretical model. Within the experimental un-
certainties, a good agreement is found between the \( R_{\text{AA}} \) measured
in the two systems and with the calculation. These results show
that the relative contribution of suppression and regeneration pro-
cesses is similar for collisions producing similar \( N_{\text{part}} \) values from
different collision systems.

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ALICE Collaboration

52 INFN, Laboratori Nazionali di Frascati, Frascati, Italy
53 INFN, Sezione di Bari, Bari, Italy
54 INFN, Sezione di Bologna, Bologna, Italy
55 INFN, Sezione di Cagliari, Cagliari, Italy
56 INFN, Sezione di Catania, Catania, Italy
57 INFN, Sezione di Padova, Padova, Italy
58 INFN, Sezione di Roma, Rome, Italy
59 INFN, Sezione di Torino, Turin, Italy
60 Inha University, Incheon, Republic of Korea
61 Institut de Physique Nucléaire d'Orsay (IPNO), Institut National de Physique Nucléaire et de Physique des Particules (IN2P3/CNRS), Université de Paris-Sud, Université Paris-Saclay, Orsay, France
62 Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
63 Institute for Subatomic Physics, Utrecht University/Nikhef, Utrecht, Netherlands
64 Institute for Theoretical and Experimental Physics, Moscow, Russia
65 Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
66 Institute of Physics, Bhubaneswar, India
67 Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
68 Institute of Space Science (ISS), Bucharest, Romania
69 Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
70 Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
71 Instituto de Fisica, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
72 Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
73 iThemba LABS, National Research Foundation, Somerset West, South Africa
74 Johann Wolfgang Goethe-Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik, Frankfurt, Germany
75 Joint Institute for Nuclear Research (JINR), Dubna, Russia
76 Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
77 KTO Karatay University, Konya, Turkey
78 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
79 Lawrence Berkeley National Laboratory, Berkeley, CA, United States
80 Lund University Department of Physics, Division of Particle Physics, Lund, Sweden
81 Nagasaki Institute of Applied Science, Nagasaki, Japan
82 Nara Women’s University (NWU), Nara, Japan
83 National and Kapodistrian University of Athens, School of Science, Department of Physics, Athens, Greece
84 National Centre for Nuclear Research, Warsaw, Poland
85 National Institute of Science Education and Research, HBNI, Jatni, India
86 National Nuclear Research Center, Baku, Azerbaijan
87 National Research Centre Kurchatov Institute, Moscow, Russia
88 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
89 Nikhef, National Institute for subatomic physics, Amsterdam, Netherlands
90 NRC Kurchatov Institute IHEP, Protvino, Russia
91 NRU Moscow Engineering Physics Institute, Moscow, Russia
92 Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
93 Nuclear Physics Institute of the Czech Academy of Sciences, Rež u Práhy, Czech Republic
94 Oak Ridge National Laboratory, Oak Ridge, TN, United States
95 Petersburg Nuclear Physics Institute, Gatchina, Russia
96 Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia
97 Physics Department, Panjab University, Chandigarh, India
98 Physics Department, University of Jammu, Jammu, India
99 Physics Department, University of Rajasthan, Jaipur, India
100 Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany
101 Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
102 Physik Department, Technische Universität München, Munich, Germany
103 Physics Department, University of Texas at Austin, Austin, TX, United States
104 Research Division and Extreme Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
105 Rudjer Bošković Institute, Zagreb, Croatia
106 Russian Federal Nuclear Center (VINIIEF), Sarov, Russia
107 Saha Institute of Nuclear Physics, Kolkata, India
108 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
109 Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
110 Shanghai Institute of Applied Physics, Shanghai, China
111 Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
112 SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, Nantes, France
113 Suranaree University of Technology, Nakhon Ratchasima, Thailand
114 Technical University of Košice, Košice, Slovakia
115 Technische Universität München, Excellence Cluster ‘Universe’, Munich, Germany
116 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
117 The University of Texas at Austin, Austin, TX, United States
118 Universidad Autónoma de Sinaloa, Culiacán, Mexico
119 Universidade de São Paulo (USP), São Paulo, Brazil
120 Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
121 Universidade Federal do ABC, Santo André, Brazil
122 University College of Southeast Norway, Tonsberg, Norway
123 University of Cape Town, Cape Town, South Africa
124 University of Houston, Houston, TX, United States
125 University of Jyväskylä, Jyväskylä, Finland
126 University of Liverpool, Department of Physics, Oliver Lodge Laboratory, Liverpool, United Kingdom
127 University of Tennessee, Knoxville, TN, United States
128 University of the Witwatersrand, Johannesburg, South Africa
129 University of Tokyo, Tokyo, Japan
University of Tsukuba, Tsukuba, Japan
Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, Lyon, France
Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000, Strasbourg, France
Université Paris-Saclay Centre d’Études de Saclay (CEA), IRFU, Département de Physique Nucléaire (DPhN), Saclay, France
Università degli Studi di Foggia, Foggia, Italy
Università degli Studi di Pavia, Pavia, Italy
Università di Brescia, Brescia, Italy
Universitá dei Studi di Foggia, Foggia, Italy
Università degli Studi di Pavia, Pavia, Italy
Università degli Studi di Foggia, Foggia, Italy
Università degli Studi di Pavia, Pavia, Italy
Università di Brescia, Brescia, Italy

i Deceased.
ii Dipartimento DET del Politecnico di Torino, Turin, Italy.
iii M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear Physics, Moscow, Russia.
iv Department of Applied Physics, Aligarh Muslim University, Aligarh, India.
v Institute of Theoretical Physics, University of Wroclaw, Poland.